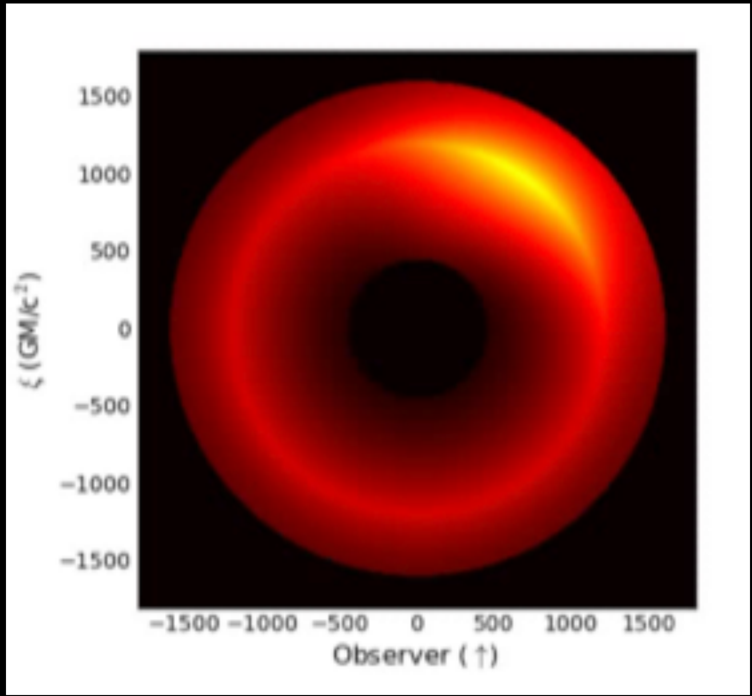

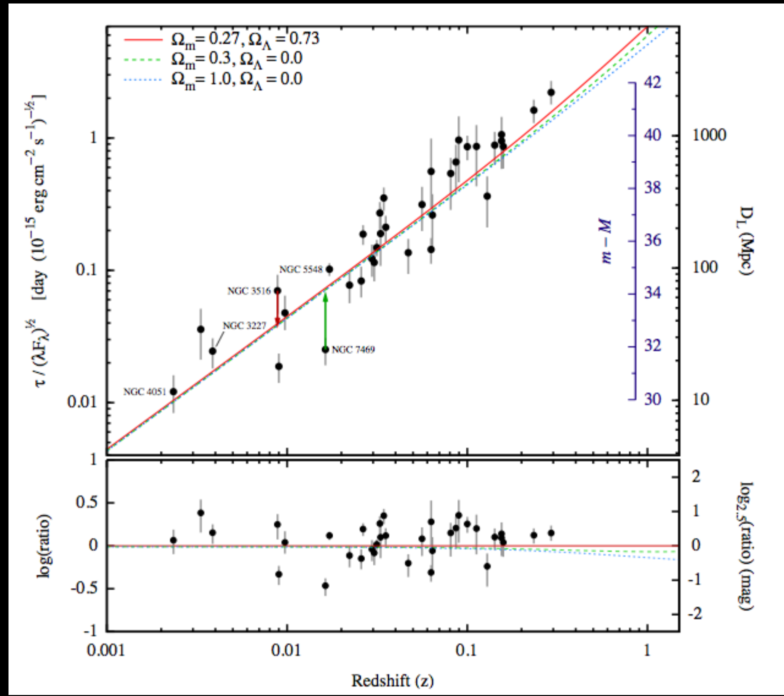

Reverberation mapping of AGN and application to Cosmology

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Collaborators

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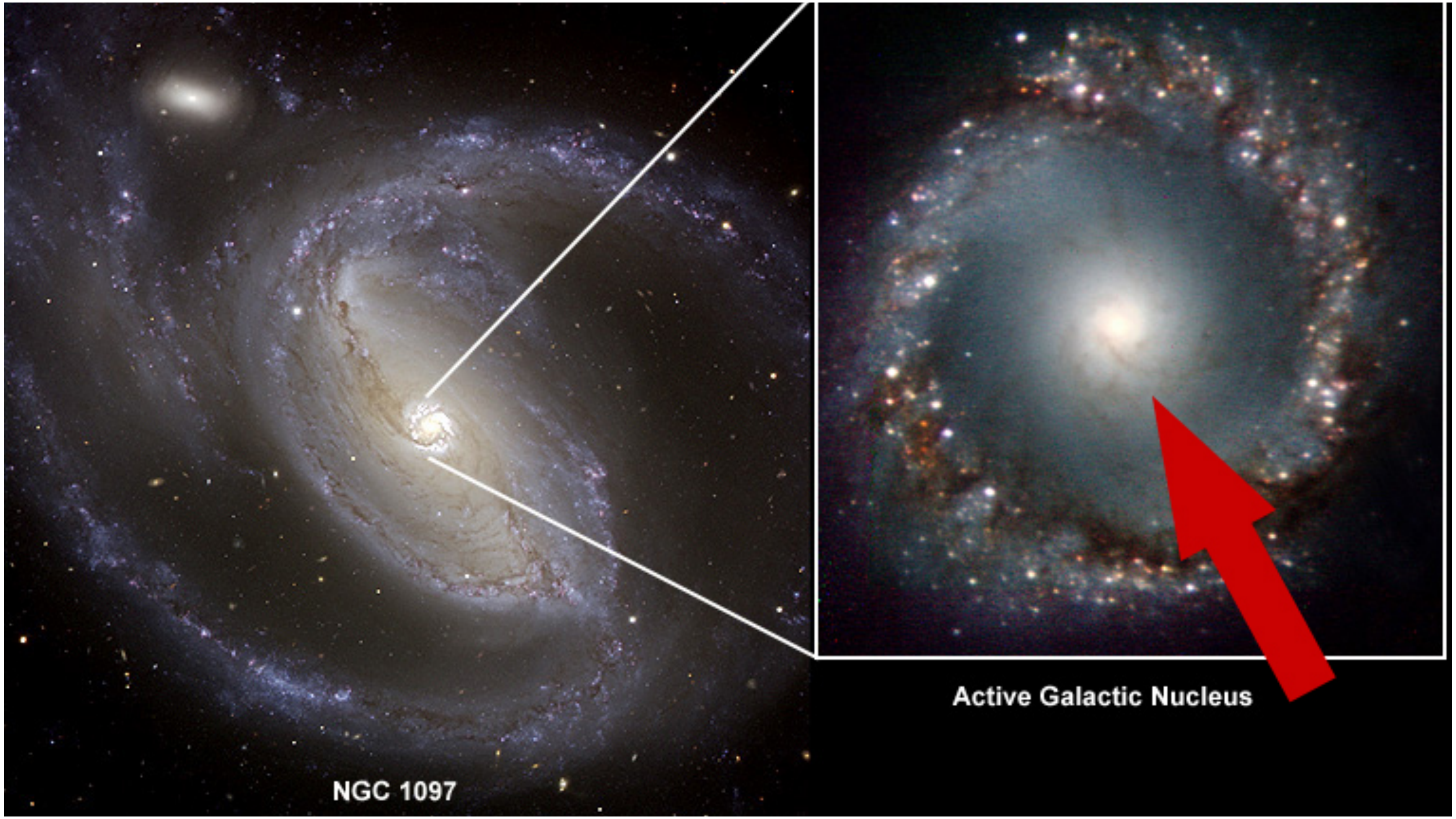
- Michael Eracleous (Penn State)
- Claudia Winge (Gemini)
- Bradley Peterson (OSU, Reverberation mapping specialist)

Outline

- The case of NGC1097: variation of broad double-peaked Hα profile (20 yrs!)
- Accretion disk as origin of the double-peaked profile
- Reverberation in the accretion disk of NGC1097
- Reverberation mapping of AGN in general
- Application to Cosmology

The case of NGC1097



Storchi-Bergmann et al. 1993

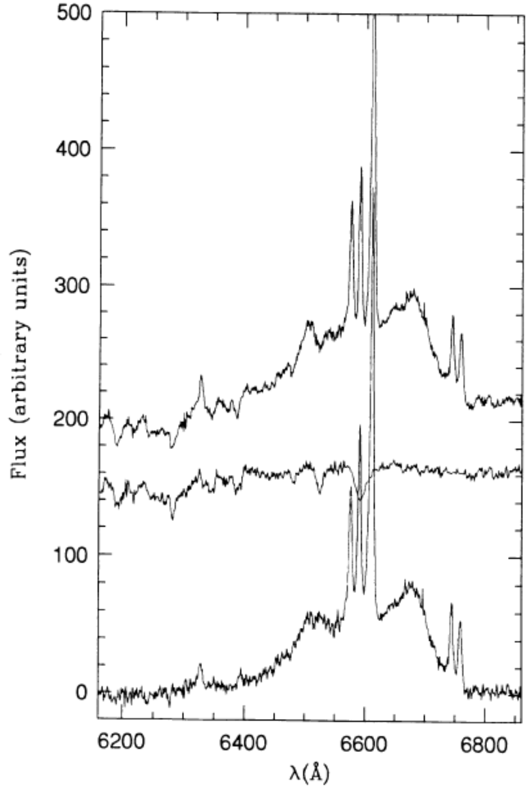
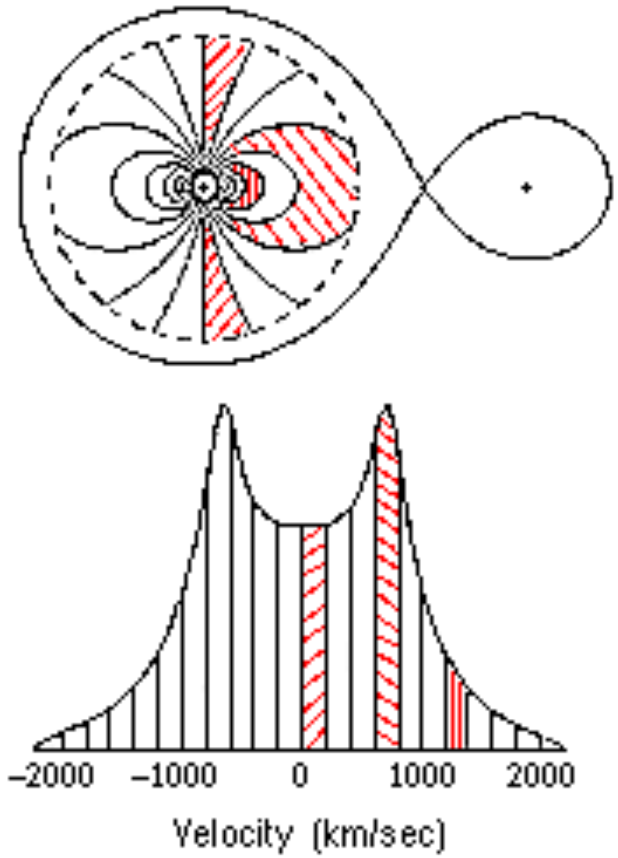


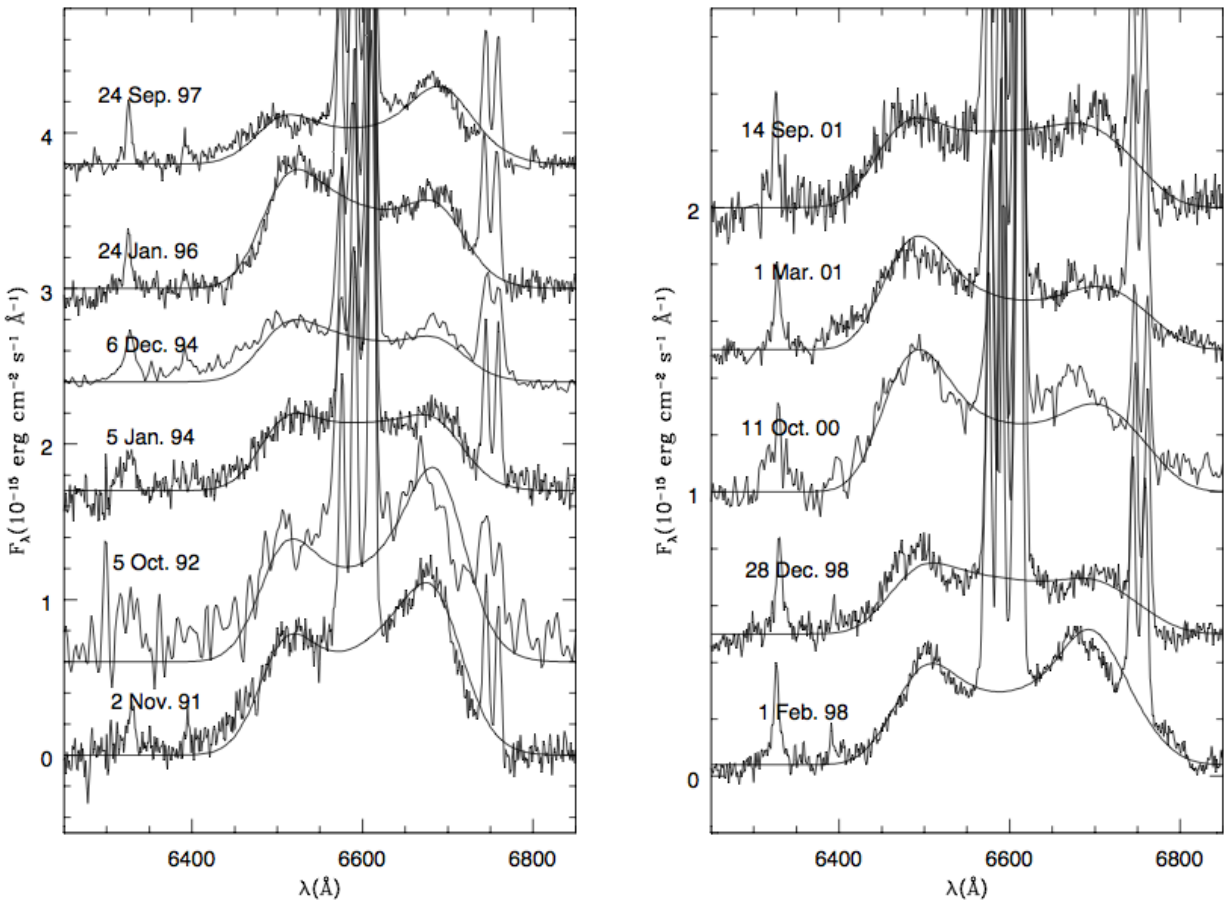
FIG. 1.—Observed nuclear high-dispersion spectrum (*top*), adopted stellar population spectrum (*middle*), and the difference observed spectrum minus stellar population (*bottom*). Two pixels along the slit were binned together, giving an effective aperture of 2″ × 1″.8 (167 × 150 pc).



Discovery of broad (10,000km/s), double-peaked Hα profile from the LINER nucleus of NGC 1097

Interpretation: emission from accretion disk, or ring (known for cataclismic variables)

Storchi-Bergmann et al. 2003



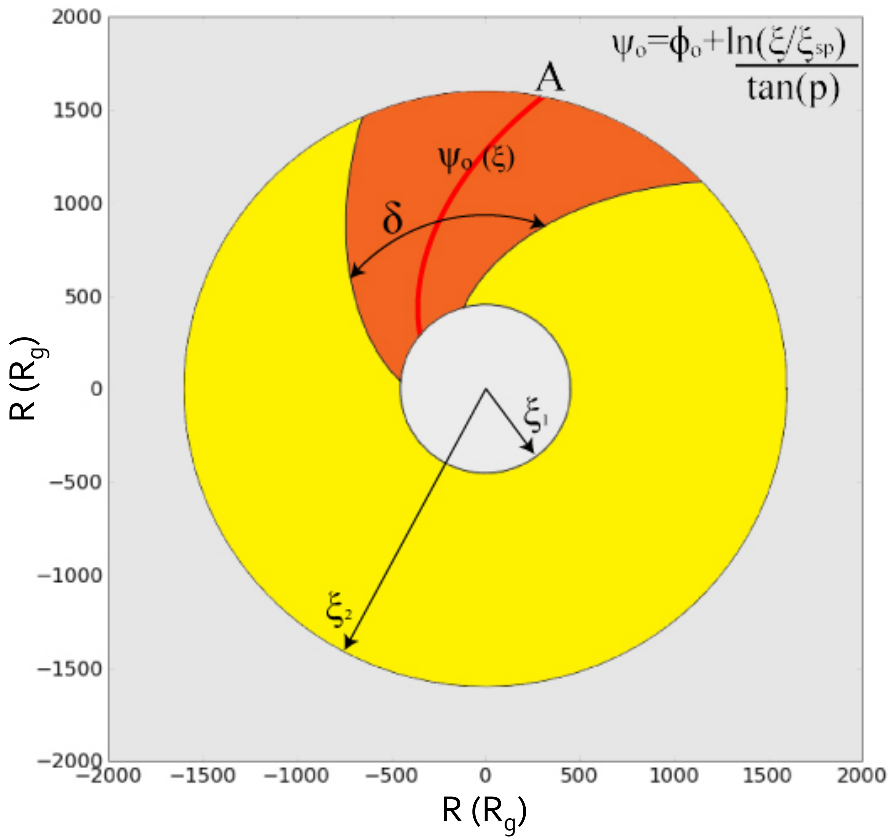
Yearly observations 1991-2001: variations of total flux, width, relative intensities of the blue and red peaks: model of a ring with one-armed spiral.

Storchi-Bergmann et al. 2003

Emissivity: $$\epsilon(\xi,\phi)=\epsilon(\xi)\left\{1+\frac{A}{2}\exp\left[-\frac{4ln2}{\delta^2}(\phi-\psi_0)^2\right]+\frac{A}{2}\exp\left[-\frac{4ln2}{\delta^2}(2\pi-\phi+\psi_0)^2\right]\right\}$$

$$\epsilon(\xi)=\xi^{-q}$$

$$I_{\nu_e}(\xi,\phi,\nu_e)=\frac{\epsilon(\xi,\phi)}{4\pi}\frac{e^{-(\nu_e-\nu_0)^2/2\sigma^2}}{(2\pi)^{1/2}\sigma},$$

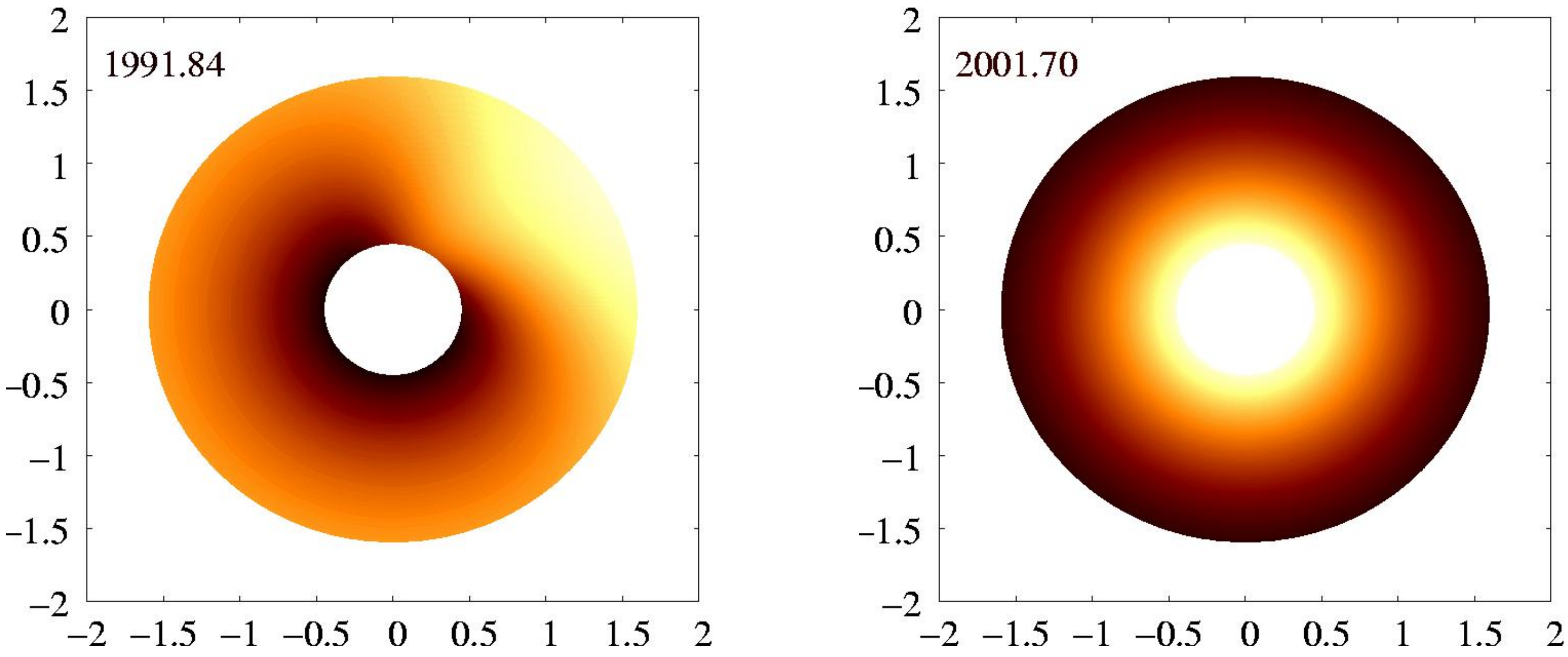


- Best fit parameters:

ξ_1= 450 R_g
ξ_2= 1600 R_g;
p=-50°
δ=70°
σ=1200 km/s

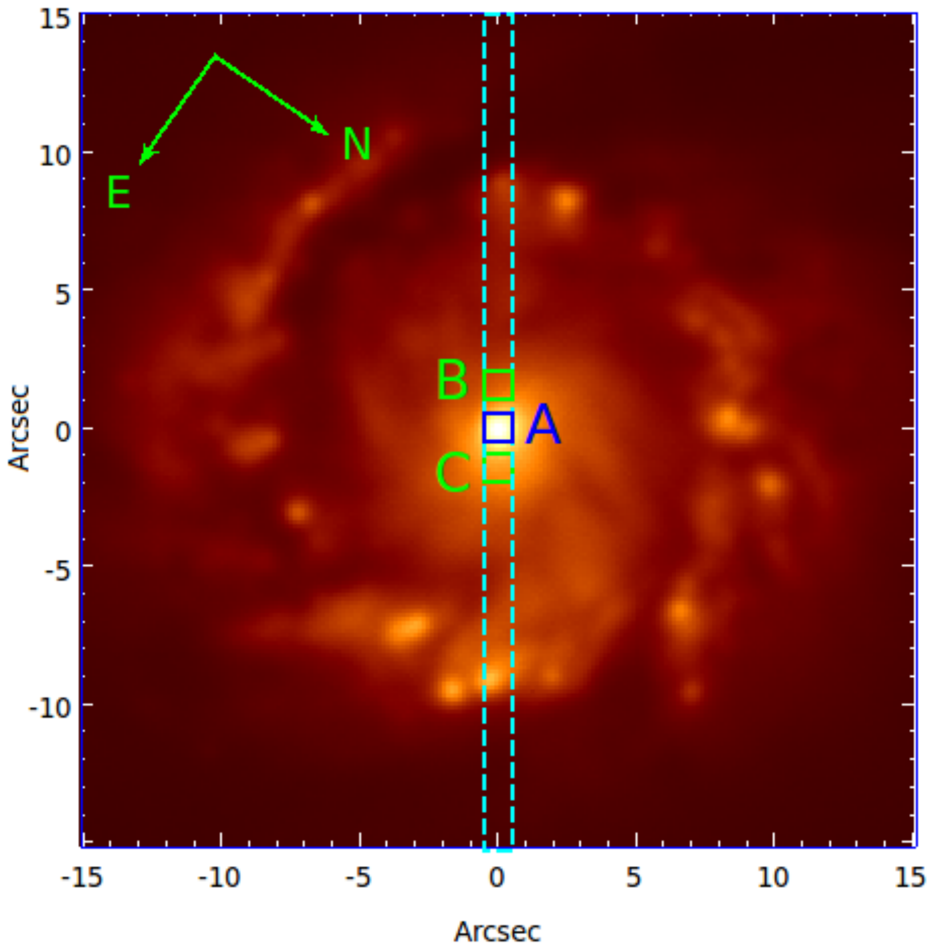
- Change in relative intensity of the peaks due to rotation of the spiral

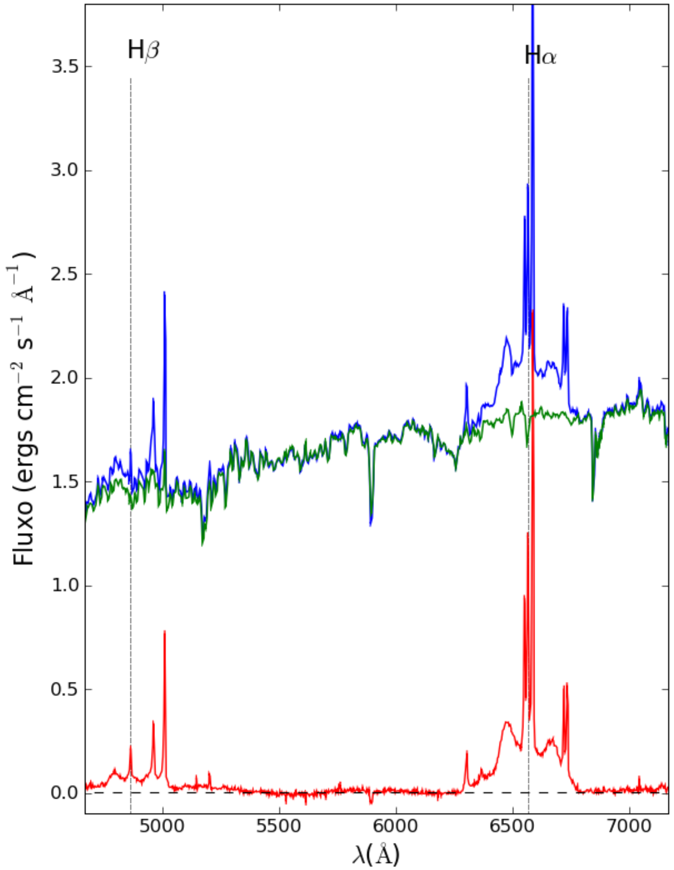
Storchi-Bergmann et al. 2003



- Change in total flux and width of the profiles due to change in emissivity

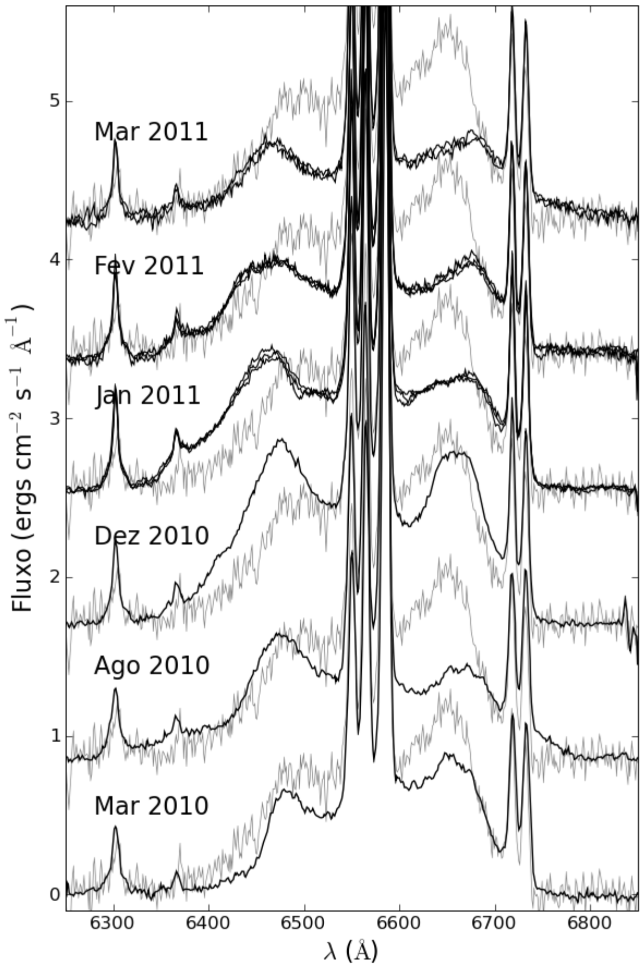
Schimoia et al. 2012, ApJ





Gemini GMOS, long-slit

Schimoia et al. 2012

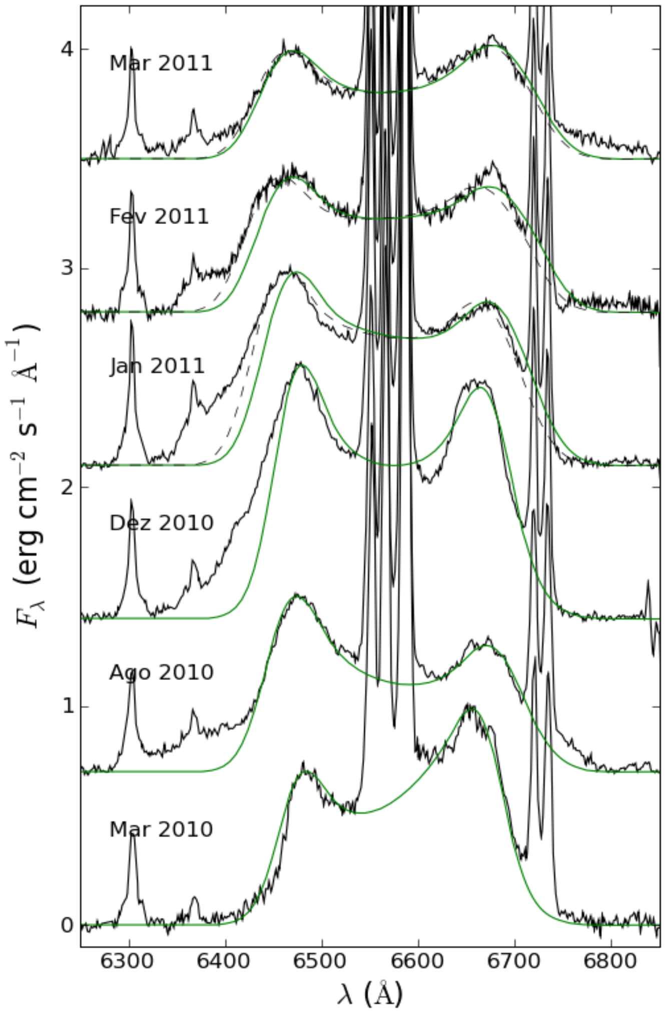


Comparison with 1991 profile

2010-2011: Gemini "poor weather" compared with 1991 profile:

- Reversal in relative intensities of two peaks in 5 months
- "Flare" in Dez. 2010
- Quick decrease in flux, with changes in a week timescale

Schimoia et al. 2012



Models of one-armed spiral as in SB2003, with "broken" emissivity law:

$$\epsilon(\xi) = \begin{cases} \epsilon_0 \xi^{-q_1} & , \xi_1 < \xi < \xi_q \\ \epsilon_0 \xi_q^{-(q_1 - q_2)} \xi^{-q_2} & , \xi_q < \xi < \xi_2 \end{cases}$$

Best fit parameters:

ξ_1 = 450 R_g

ξ_2 = 1600 R_g;

p=-50°

δ=70°

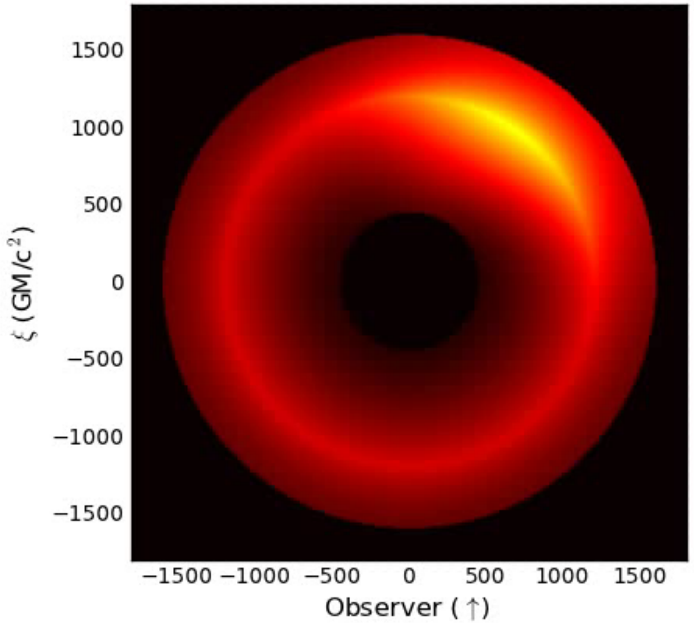
σ=1200 km/s

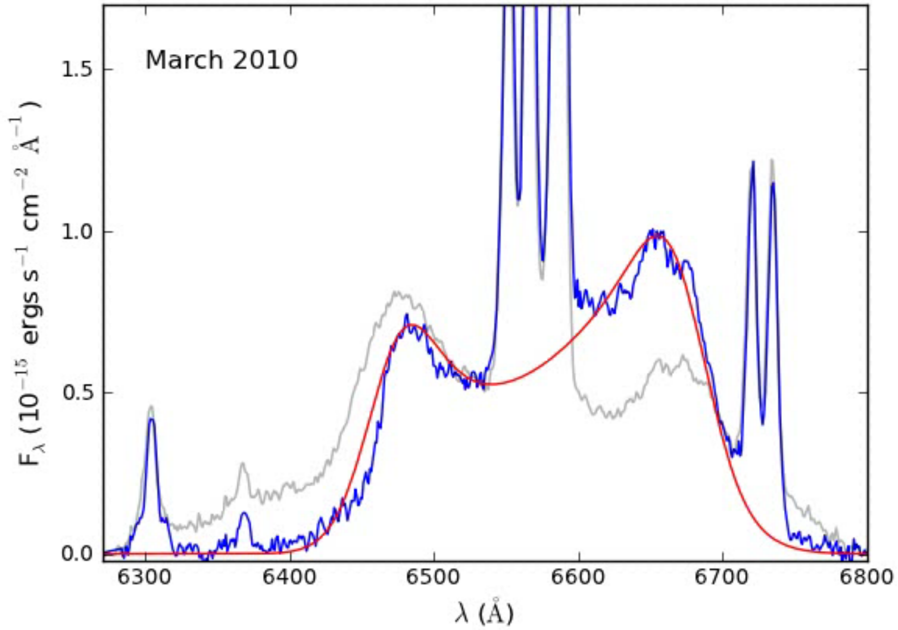
q1=-2

q2=3

Varying parameters: ξ_q , A, Φ_o

Schimoia et al. 2012





Cartoon: sequence of models: rotation of the spiral and change in emissivity

Corresponding modeled profiles compared with data

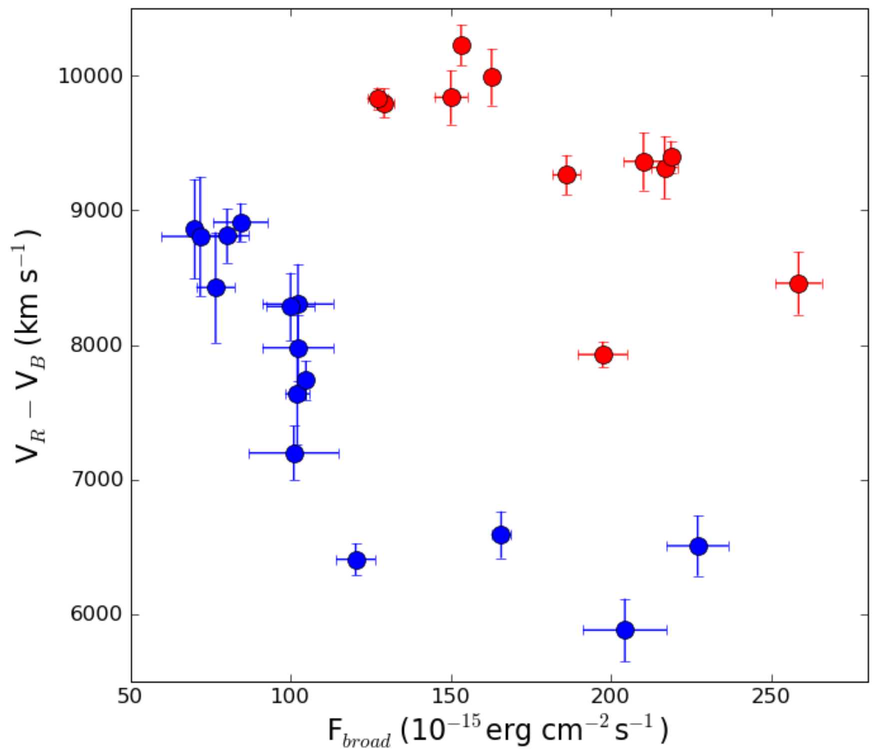
Schimoia et al. 2012

Further results:

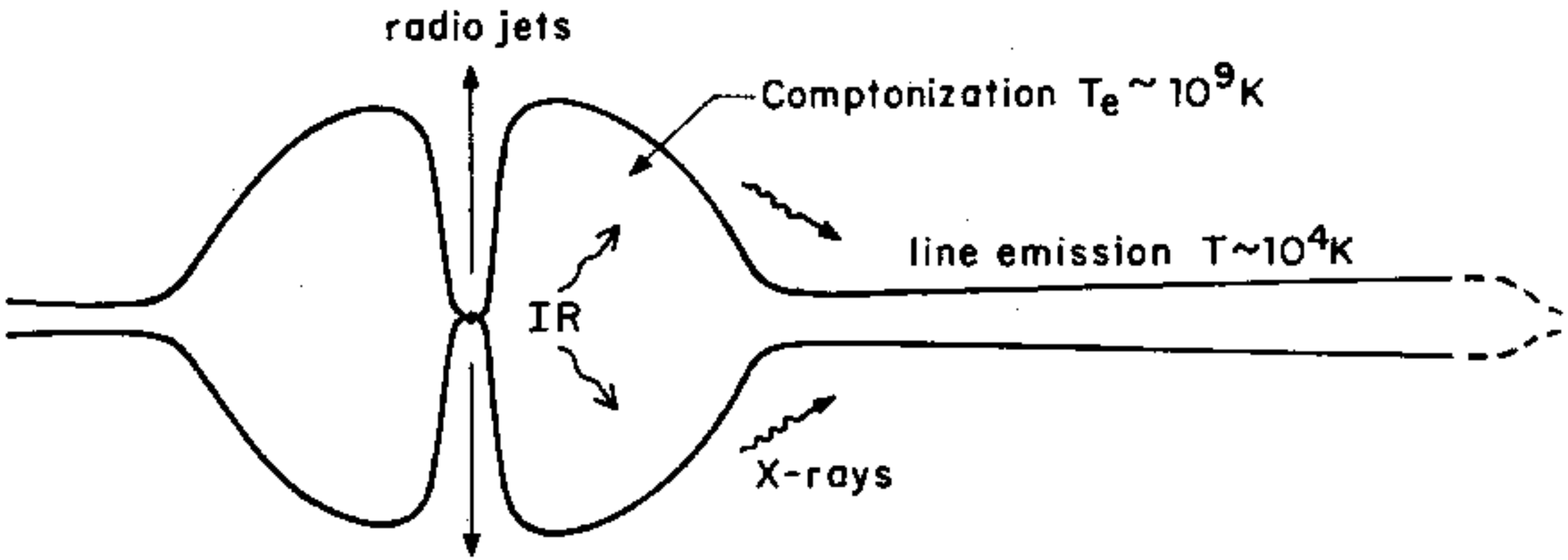
- Rotation period of the spiral: 17.5±1 months
- Inverse correlation between velocity difference of the peaks and integrated line flux:

➡ response to ionizing flux coming from the inner regions (reverberation):

(1) stronger flux ionizes farther away (lower velocities) and profile is narrower;
(2) weaker flux reaches regions closer to the source and profile is broader



Nemmen et al. 2007



SED (in particular, X-rays) well described by RIAF (Radiatively Ineficient Accretion Flow): inner RIAF drives the line emission in the disk;

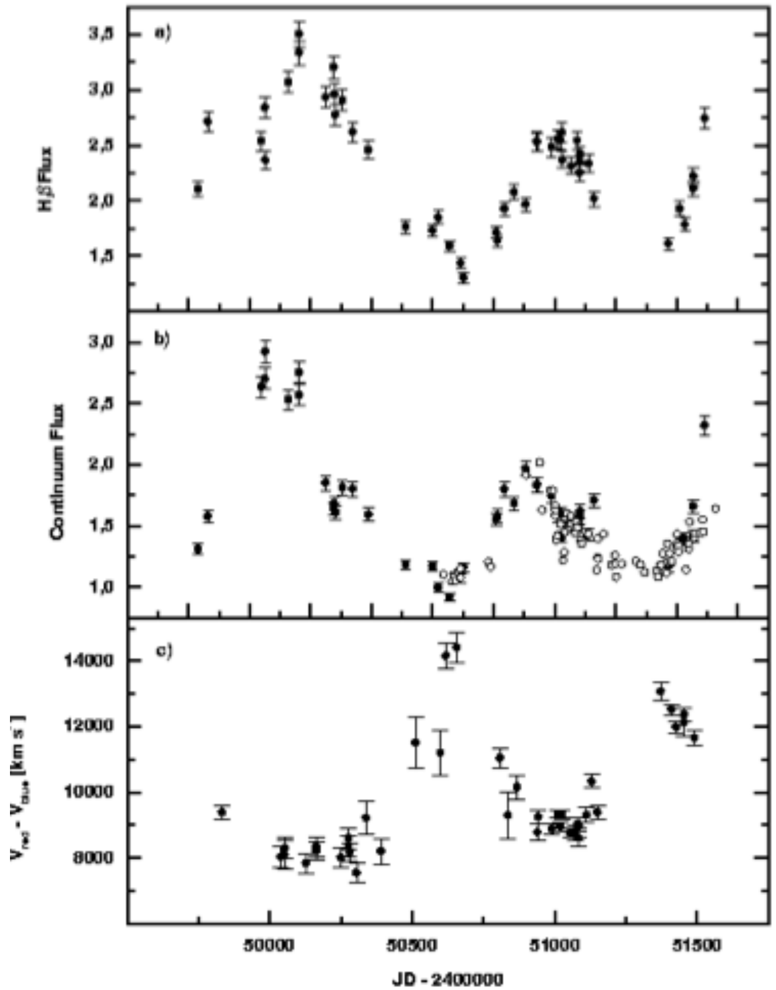
➡ Next step: reverberation mapping: observations in X-rays, UV and optical continuum simultaneous to spectroscopy to cross-correlate with variations in the profile

Prediction: ~7 days delay (mean radius of the ring is about 7 light-days) -> independent measure of the mass of the SMBH

Reverberation mapping of 3C390.3

Reverberation in a "double-peaker":
Shapovalova et al. 2001:

- Flux variation in Hβ lag the one in the continuum (5100A) -> delay is a measure of the mean radius of the emitting ring -> measure of the black hole mass
- Inverse correlation between flux and width of the profile, as in NGC1097



Use of LSST

1. LSST light curves in the continuum of sample of "double-peakers" can be used together with spectroscopic monitoring (restricted wavelength range) to allow reverberation mapping

2. Profile variations are strongest when fluxes are highest -> LSST observations to spot increase in continuum flux and trigger spectroscopic follow up

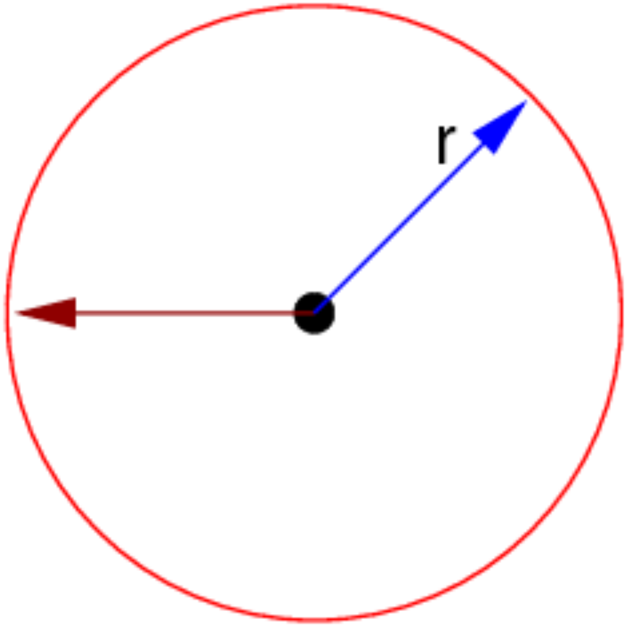
Cosmology with Reverberation Mapping of AGN

Bradley Peterson and collaborators:

Simultaneous observation of the continuum from nuclear source and broad lines from gas at a distance *r* (the so-called Broad Line Region – BLR):

Radiation flash of a central source at t=0 will illuminate (ionize) gas at a distance *r* after a time delay: $\tau = r/c$

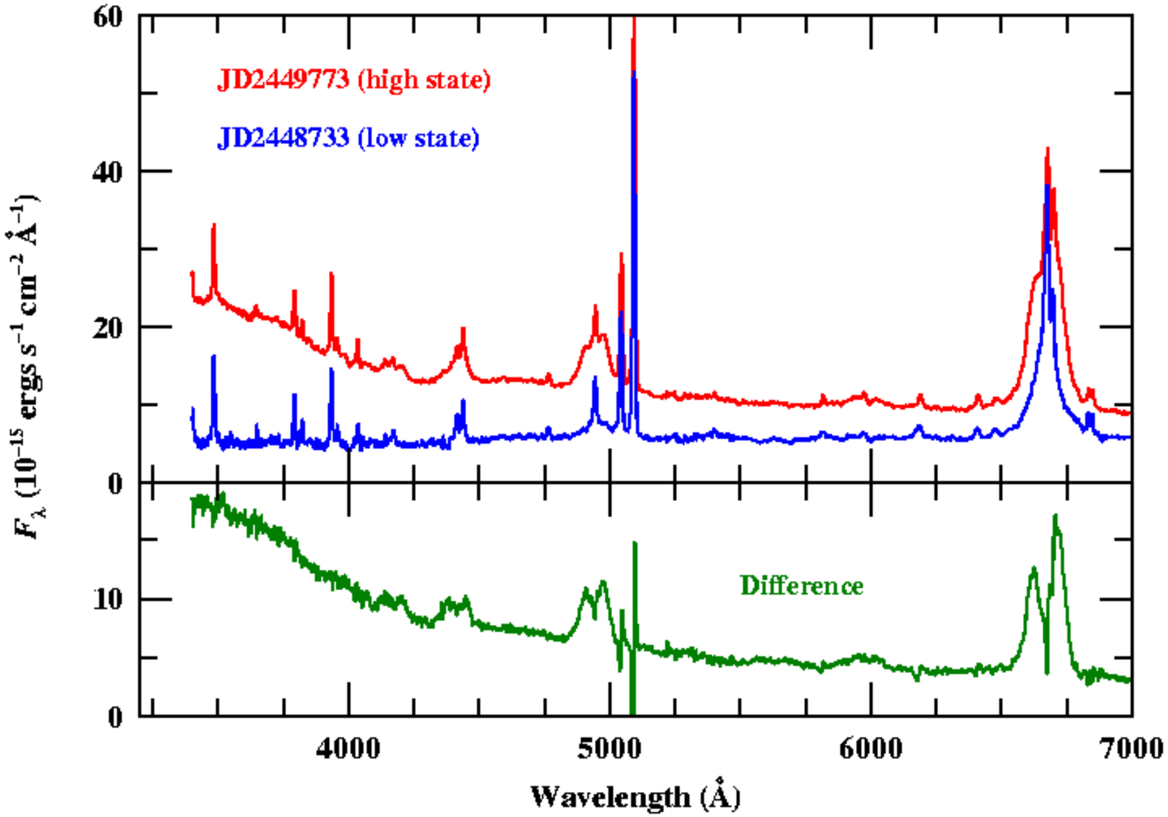
Thus delay is a measure of the distance of the emitting clouds: R_{BLR}



Reverberation mapping of NGC5548

Peterson 2000's:

Seyfert 1 galaxy NGC5548: spectra at "high" and "low" states



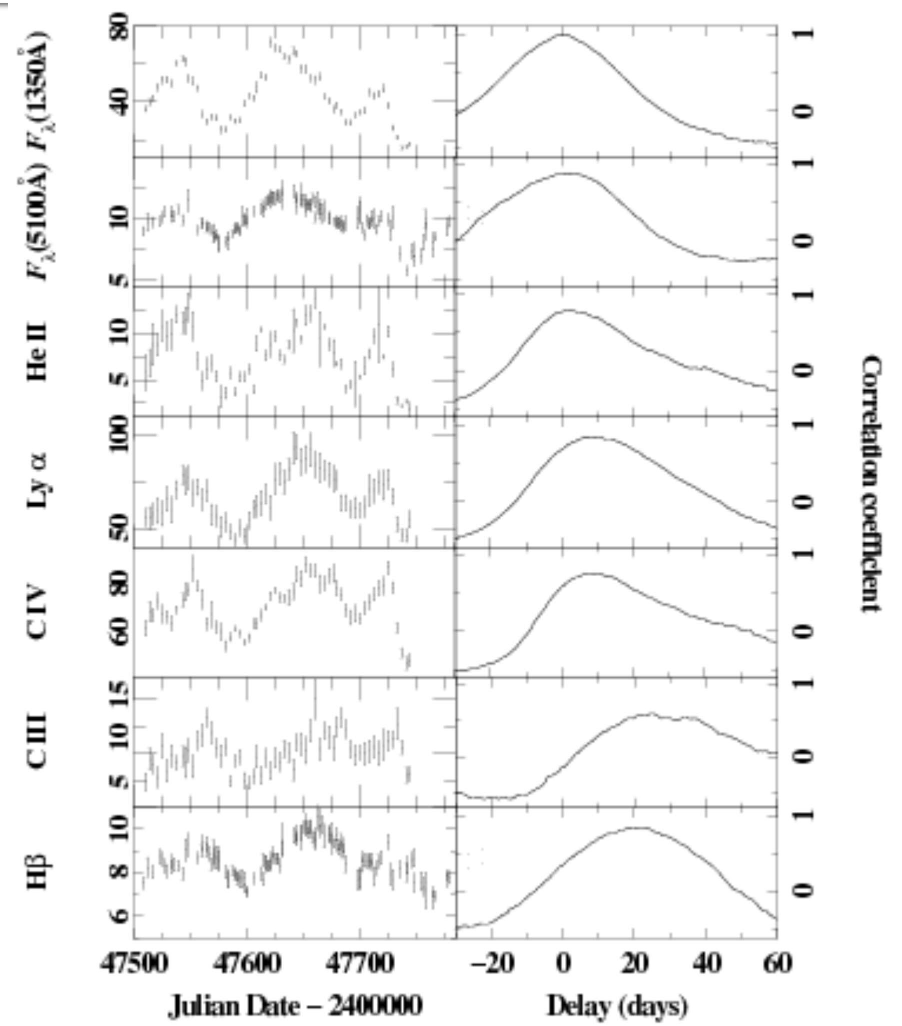
Reverberation mapping of NGC5548

Clavel et al. 1992, Peterson 2001:

- Variation of emission-line fluxes lag variation of the continuum;
- Delay determined by peak of cross-correlation function:

20 days for Hβ and 7 days for CIV (UV)

-> sizes of corresponding emitting regions



Size vs. Luminosity relation

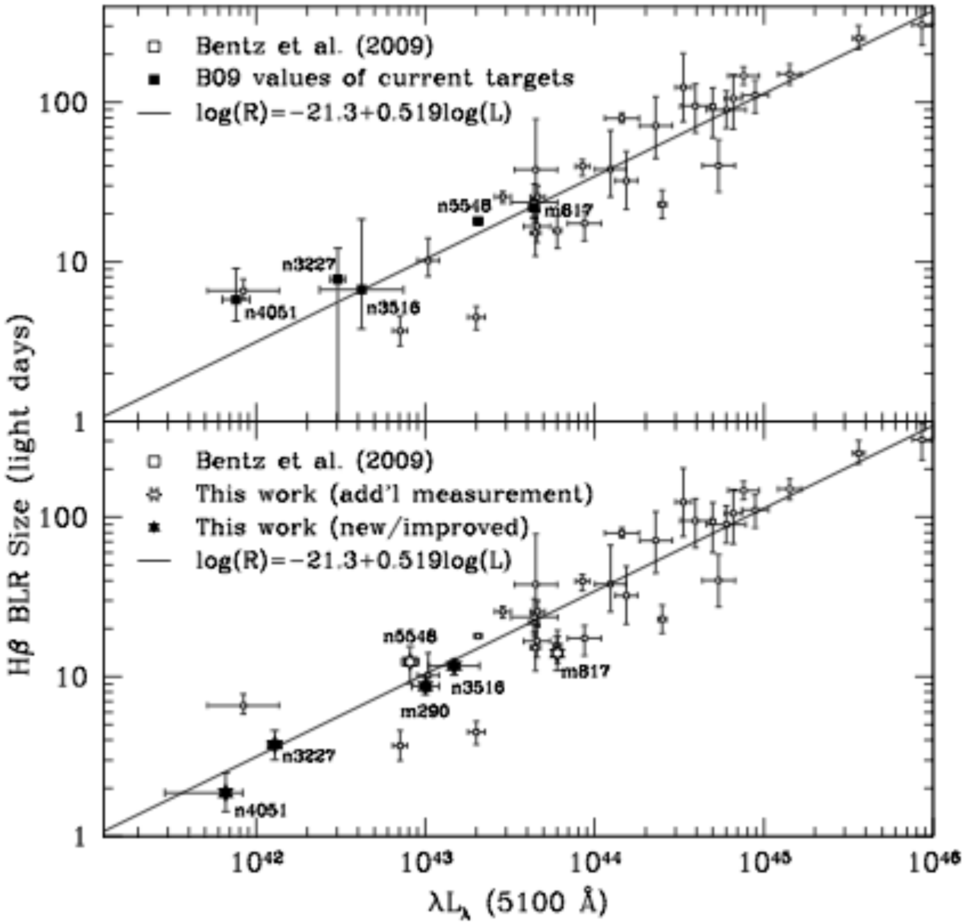
Peterson 2010: ~50 AGN

Kaspi (2000,2005); Bentz et al. 2009: Size vs. Lum. relation: $R_{BLR} \alpha L^{0.5}$

Expected for U and n_e constant ($U \alpha L/R^2 n_e$)

Measuring R_{BLR} -> L(5100A)

➡ Luminosity distance!



Denney et al. 2010

Use for Cosmology

Watson et al. 2011:

delay τ -> R_{BLR} -> L -> D_L

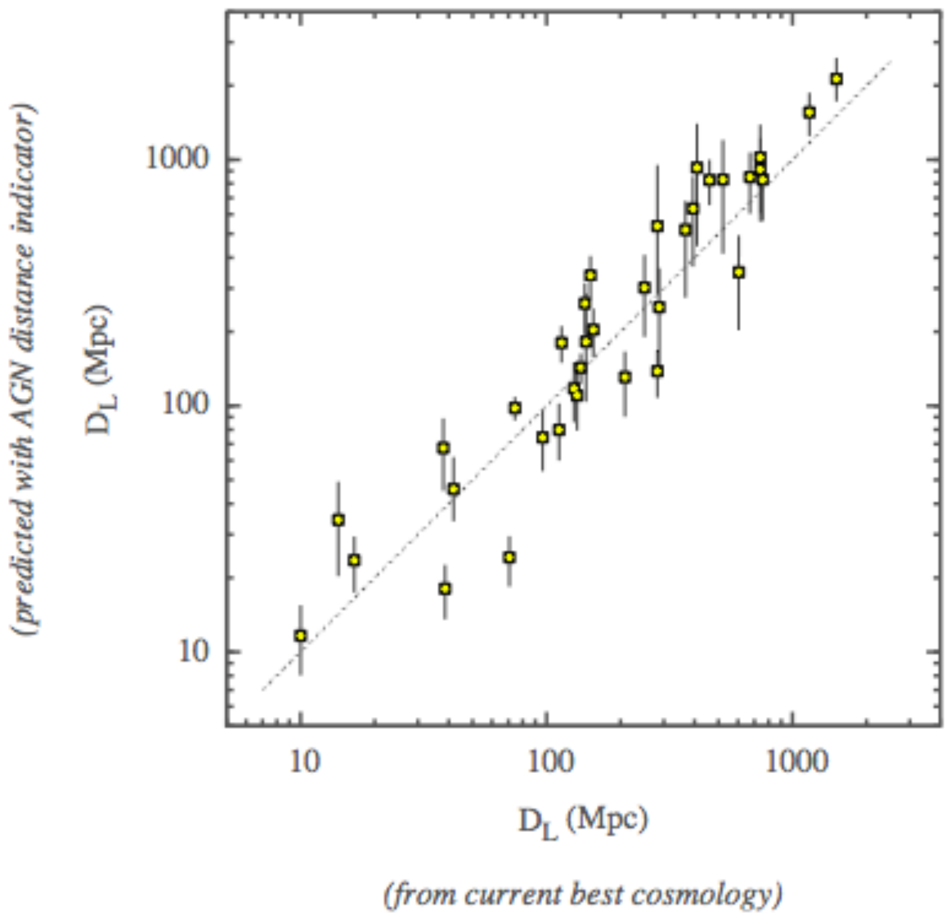


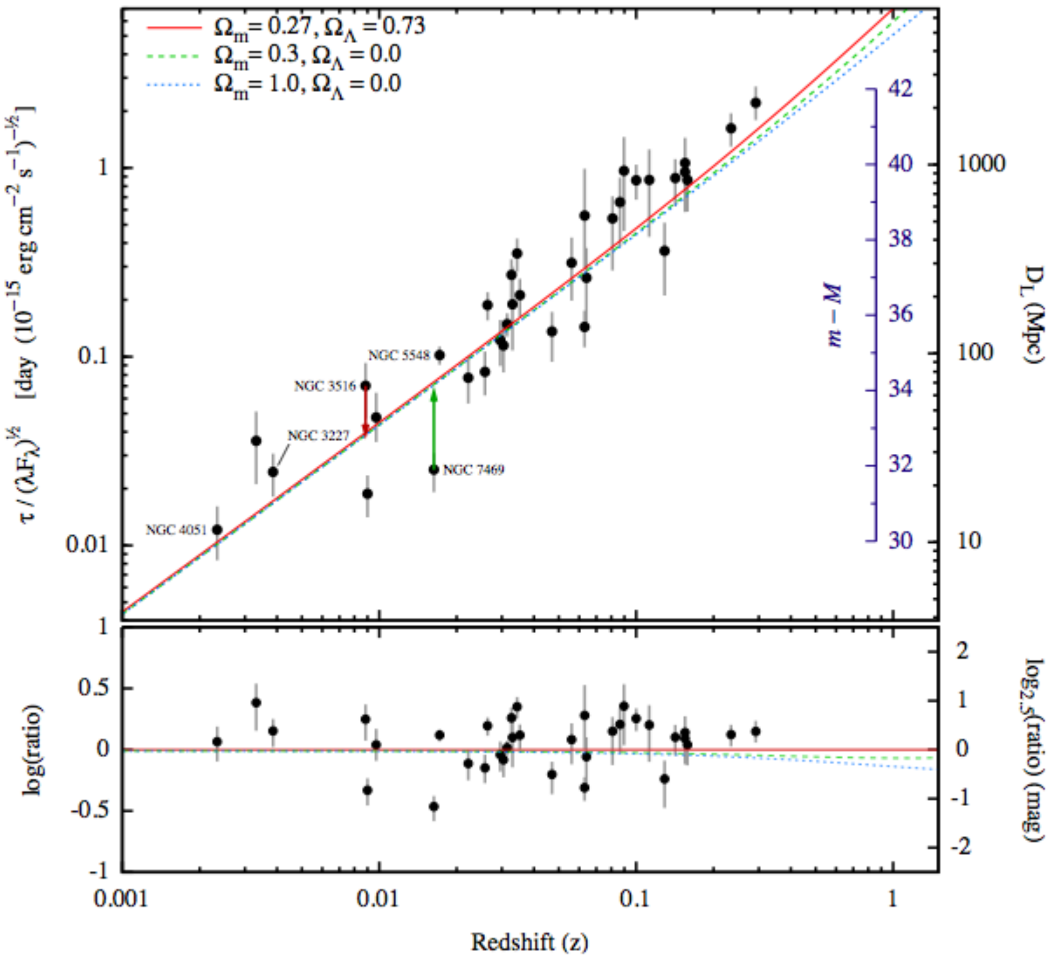
FIG. 1.— Comparison of AGN-derived distances to Hubble distances based on the best current cosmology (Komatsu et al. 2011). The dotted line is the equality of both distances. The AGN distance estimates follow the best current cosmology Hubble distances to good accuracy

Use for Cosmology: AGN Hubble diagram

Watson et al. 2011:

Using CIV (1549A) in the UV: varying QSOs can be observed in the optical up to z~4, much farther than SNe's

Lags are larger for QSOs (plus time dilation), but shorter for CIV than Hβ



Use of LSST

1. LSST light curves of sample of QSOs can be used together with spectroscopic monitoring to allow reverberation mapping -> SMBH masses

2. Profile variations are strongest when fluxes are highest -> LSST observations to spot increase in continuum flux and trigger spectroscopic follow up

3. Delays -> R_{BLR} -> D_L of QSOs up to z=4